Constraints on Neutrino Interactions at energies beyond 100 PeV with Neutrino Telescopes

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***Abstract*. A search for extremely high energy cosmic neutrinos has been carried out with the IceCube Neutrino Observatory. These event are neutrino-induced energetic charged leptons and their rate depends on the neutrino-nucleon cross-sections. The resultant event rate has implications for possible new physics beyond the standard model as it is predicted that the cross-sections can be much higher than the standard particle physics prediction if we live in more than four space-time dimensions. In this study we show the capability of neutrino telescopes such as IceCube to constrain neutrino cross-sections at energies beyond 10^7 GeV. The constraints are obtained as a function of the extraterrestrial neutrino flux in the relevant energy range, which accounts for the astrophysical uncertainty of neutrino production models.**

***Keywords*: Neutrino, IceCube, cross-sections**

I. Introduction

High energy cosmic neutrino observations provide a rare opportunity to explore the neutrino-nucleon (νN) interaction behavior beyond energies accessible by the present accelerators. These neutrinos interact druing their propagation in the earth and produce energetic muons and taus. These secondary leptons reach underground neutrino detectors and leave the detectable signals. The detection rate is, therefore, sensitive to neutrino-nucleon interaction probability. The center-of-mass energy of the collision, $\sqrt{s}$, is well above ~ 10 TeV for cosmic neutrino energies on the order of 1 EeV ($= 10^9$ GeV), a representative energy range for the bulk of the GZK cosmogenic neutrinos, generated by the interactions between the highest energy cosmic ray nucleons and the cosmic microwave background photons [1].

The νN collision cross-sections can be varied largely if non-standard particle physics beyond the Standard Model (SM) are considered in the high energy regime of $\sqrt{s} \gg$ TeV. The extra-dimension scenarios, for example, have predicted such effects [2]. The cross-sections of black hole productions via νN collisions can be larger than the SM prediction by more than two orders of magnitude [3]. The effect would be sizable enough to affect the expected annual event rate ($O(0.1-1)$) of the GZK neutrinos by $\sim$ km^3 instrumentation volume of the underground neutrino telescope such as the IceCube observatory, thereby the search for the extremely-high energy (EHE) cosmic neutrinos leads to constraints on the non-standard particle physics.

The IceCube neutrino observatory has already begun EHE neutrino hunting with the partially deployed underground optical sensor array. The 2007 partial IceCube detector realized a ~ 0.5 km^2 effective area for muons with 10^9 GeV and recently placed a limit on the flux of EHE neutrinos at the level approximately an order of magnitude higher than the expected GZK cosmogenic neutrino intensities for 242 days of observation [4]. Since new particle physics may vary the cross section by more than an order of magnitude as we noted above, this result should already imply a meaningful bound on the νN cross-sections. In this paper, we study the constraint on the νN cross-sections ($\sigma_{\nu\mathrm{N}}$) by the null detection of EHE neutrinos with the 2007 IceCube observation. A model-independent bound is derived by estimating the lepton intensity at the IceCube depth with the SM cross-sections scaled by a constant. The constraint is displayed in form of the excluded region on the plane of the cosmic neutrino flux and $\sigma_{\nu\mathrm{N}}$. It is equivalent to upper-bound of $\sigma_{\nu\mathrm{N}}$ for a given flux of astrophysical EHE neutrinos.

II. The Method

The neutrino and charged lepton fluxes at the IceCube depth originated in a given neutrino flux at are calculated by the coupled transportation equations:

$$\begin{aligned}\frac{dJ_\nu}{dX} &= -N_A\sigma_{\nu N,CC+NC}J_\nu + \frac{m_l}{c\rho\tau_l^d}\int dE_l \frac{1}{E_l}\frac{dn_l^d}{dE_\nu}J_l(E_l)\\ &+N_A\int dE_\nu^{'}\,\frac{d\sigma_{\nu N,NC}}{dE_\nu}J_\nu(E_\nu^{'})\\ &+N_A\int dE_l^{'}\,\frac{d\sigma_{lN,CC}}{dE_\nu}J_l(E_l^{'}) \qquad (1)\\ \frac{dJ_l}{dX} &= -N_A\sigma_{lN}J_l - \frac{m_l}{c\rho\tau_l^d E_l}J_l\\ &+N_A\int dE_\nu^{'}\frac{d\sigma_{\nu N,CC}}{dE_l}\,J_\nu(E_\nu^{'})\\ &+N_A\int dE_l^{'}\frac{d\sigma_{lN}}{dE_l}J_l(E_l^{'})\\ &+\frac{m_l}{c\rho\tau_l^d}\int dE_l^{'}\,\frac{1}{E_l^{'}}\frac{dn_l^d}{dE_l}J_l(E_l^{'}), \qquad (2)\end{aligned}$$

where $J_l = dN_l/dE_l$ and $J_\nu = dN_\nu/dE_\nu$ are differential fluxes of charged leptons and neutrinos, respectively. X is the column depth, N_A is the Avogadro's number, ρ is the local density of the medium (rock/ice) in the propagation path, σ is the relevant interaction cross-sections, dn_l^d/dE is the energy distribution of the decay products which is derived from the decay rate per unit energy, c is the speed of light, m_l and τ_l^d are the mass

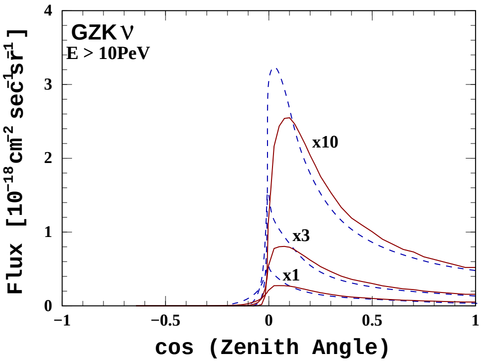

Fig. 1. Integral fluxes of the muon and taus above 10 PeV ($= 10^7$ GeV) at IceCube depth ($\sim$ 1450m) of the GZK cosmogenic neutrinos [5]. The solid lines represent the muons while the dashed lines represent the taus. Numbers along each of the curves are the multiplication factors ($\mathrm{N_{scale}}$) that enhance the standard νN cross-sections [6] in the relevant calculations.

and the decay life time of the lepton l, respectively. In this paper we scale $\sigma_{\nu\mathrm{N}}$ to that of the SM prediction with the factor $\mathrm{N_{scale}}$, *i.e.*, $\sigma_{\nu\mathrm{N}} \equiv \mathrm{N_{scale}}\sigma_{\nu\mathrm{N}}^{\mathrm{SM}}$. It is an extremely intensive computational task to resolve the coupled questions above for every possible values of $\sigma_{\nu\mathrm{N}}$. To avoid this difficulty, we introduce two assumptions to decouple calculation of J_ν from the charged lepton transportation equation. The first is that distortion of the neutrino spectrum by the neutral current reaction is small and the other is that the contribution of muon and tau decay to enhance the neutrino flux, which is represented by the second term on the right hand side of Eq. 1, is negligible. These are very good approximation in the energy region above 10^8 GeV where even the tau is unlikely to decay before reaching the IceCube instrumentation volume. Then the neutrino flux is simply given by the beam dumping factor as

$$J_\nu(\mathrm{E}_\nu, \mathrm{X_{IC}}) = J_\nu(\mathrm{E}_\nu, 0)e^{-N_{\mathrm{scale}}\sigma_{\nu\mathrm{N}}^{SM,CC}\mathrm{X_{IC}}}, \quad (3)$$

where $\mathrm{X_{IC}}$ is column density of the propagation path from the earth surface to the IceCube depth. The charged lepton fluxes, $J_{l=\mu,\tau}(\mathrm{E_l}, \mathrm{X_{IC}})$, are obtained as

$$J_{\mu,\tau}(\mathrm{E}_{\mu,\tau}, \mathrm{X_{IC}}) = N_A \int_0^{\mathrm{X_{IC}}} dX \int dE'_{\mu,\tau} \frac{dN_{\mu,\tau}}{dE_{\mu,\tau}} (\mathrm{E}'_{\mu,\tau} \rightarrow \mathrm{E}_{\mu,\tau})$$
$$\int d\mathrm{E}_\nu \mathrm{N_{scale}} \frac{d\sigma_{\nu N}^{SM,CC}}{dE'_{\mu,\tau}} J_\nu(\mathrm{E}_\nu, 0)e^{-N_{\mathrm{scale}}\sigma_{\nu\mathrm{N}}^{SM,CC}\mathrm{X}}. \quad (4)$$

Here $dN_{\mu,\tau}/dE_{\mu,\tau}(\mathrm{E}'_{\mu,\tau} \rightarrow \mathrm{E}_{\mu,\tau})$ represents distributions of muons and taus with energy of $\mathrm{E}_{\mu,\tau}$ at $\mathrm{X_{IC}}$ originated in those with energy of $\mathrm{E}'_{\mu,\tau}$ produced by νN collisions at depth X. This is calculated in the transportation equation, Eq. 2, with a replacement of $J_\nu(E'_\nu)$ by Eq. 3.

Calculation of the neutrino and the charged lepton fluxes with this method is feasible for a wide range of $\mathrm{N_{scale}}$ without any intensive computation. A comparison of the calculated fluxes with those obtained without the introduced simplification for a limited range of $\mathrm{N_{scale}}$ indicates that the relative difference we found in the resultant $J_{\nu,\mu,\tau}(X_{IC})$ is within 40%. Since this analysis is searching for at least an *order* of magnitude difference in $\sigma_{\nu\mathrm{N}}$, the introdced simplifications provide sufficient accuracy for the present study.

Fig. 1 shows the calculated intensities of the secondary muons and taus for various $\mathrm{N_{scale}}$ factors. One can see that the intensity is almost proportional to $\mathrm{N_{scale}}$ as expected since the interaction probability to generate muons and taus linearly depends on $\sigma_{\nu\mathrm{N}}$. It should be pointed out, however, that the dependence starts to deviate from the complete linearity when the propagation distance is comparable to the mean free path of neutrinos, as one can find in the case of $\mathrm{N_{scale}} = 10$ in the figure. This is because the neutrino beam dumping factor in Eq. 3 becomes significant under this circumstances.

The flux yield of leptons, Y_ν^l ($l = \nu'$s, μ, τ) from neutrinos with a monochromatic energy at earth surface, E_ν^s, is given by Eq. 4 with an insertion of $J_\nu(E_\nu, 0) = \delta(E_\nu - E_\nu^s)$. The resultant event rate per *neutrino energy decade* is then obtained by,

$$N_\nu(E_\nu^s) = \sum_{\nu=\nu_e,\nu_\mu,\nu_\tau} \frac{1}{3} \frac{dJ_{\nu_e+\nu_\mu+\nu_\tau}}{d\log E_\nu}(E_\nu^s) \int d\Omega$$
$$\sum_{l=\nu,\mu,\tau} \int dE_l A_l(E_l)\, Y_\nu^l(E_\nu^s, E_l, \mathrm{X_{IC}}(\Omega), \mathrm{N_{scale}}) \quad (5)$$

where A_l is the effective area of the IceCube to detect the lepton l. Note that the differential limit of the neutrino flux is given by Eq. 5 for $\mathrm{N_{scale}} = 1$ with $N_\nu = \bar{\mu}_{90}$ which corresponds to the 90 % confidence level average upper limit. This calculation is valid when the cosmic neutrino flux J_ν and the cross section $\sigma_{\nu\mathrm{N}}$ do not rapidly change over a decade of neutrino energy around E_ν^s. Limiting $\sigma_{\nu\mathrm{N}}$ in the present analysis corresponds to an extraction of the relation between $\mathrm{N_{scale}}$ and the (unknown) cosmic neutrino flux $J_{\nu_e+\nu_\mu+\nu_\tau}$ yielding $N_\nu = \bar{\mu}_{90}$. The obtained constraints on $\sigma_{\nu\mathrm{N}}$ is represented as a function of $J_{\nu_e+\nu_\mu+\nu_\tau}$ for a given energy of E_ν^s. It consequently accounts for astrophysical uncertainties on the cosmic neutrino flux.

In scenarios with extra dimensions and strong gravity, Kaluza-Klein gravitons can change only the neutral current (NC) cross-sections because gravitons are electrically neutral. Any scenarios belonging to this category can be investigated by scaling only $\sigma_{\nu\mathrm{N}}^{NC}$ in the present analysis. The event rate calculation by Eq. 5 is then performed for $Y_\nu^l(\mathrm{N_{scale}} = 1)$ with effective area for ν's, A_ν, enhanced by $(\sigma_{\nu\mathrm{N}}^{SM,CC} + \mathrm{N_{scale}}\sigma_{\nu\mathrm{N}}^{SM,NC})/(\sigma_{\nu\mathrm{N}}^{SM,CC} + \sigma_{\nu\mathrm{N}}^{SM,NC})$ since the rate of detectable events via the NC reaction by IceCube is proportional to $\sigma_{\nu\mathrm{N}}^{NC}$. We also show the constraint in this case.

III. Results

In this analysis we use the IceCube observation results with 242 days data in 2007 to limit $\sigma_{\nu\mathrm{N}}$ using Eq. 5. No detection of signal candidates in the measurement has led to an upper limit of the neutrino flux at 6×10^{-7}

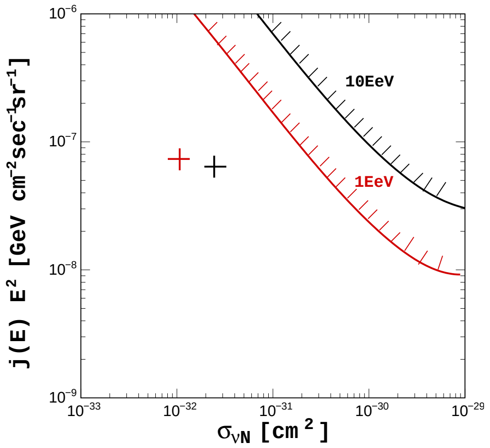

Fig. 2. Constraints on the all-flavor cosmic neutrino flux and the charged current νN cross-sections based on the null detection of neutrino signals by the IceCube 2007 observation. The right upper region is excluded by the present analysis. The cross points provide reference points where the standard cross section [6] and the expected GZK cosmogenic neutrino fluxes [7] is located.

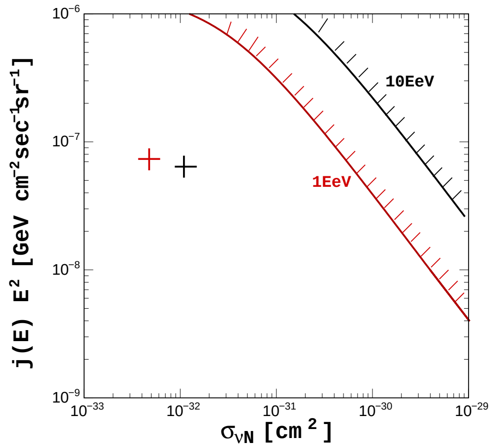

Fig. 3. Constraints on the all-flavor cosmic neutrino flux and the neutral current νN cross-sections for the scenario that only the neutral current reaction is enhanced by a new physics beyond the standard model. The right upper region is excluded by the present analysis. The crosses provide reference points for the standard cross section [6] and the expected GZK cosmogenic neutrino fluxes [7] is located.

GeV cm^{-2} sec^{-1} sr^{-1} [4]. The effective area A_l is 0.5 km^2 for μ, 0.3 km^2 for τ, and 3×10^{-4} km^2 for $\nu^{'}$s. Constraints on $\sigma_{\nu \mathrm{N}}$ are then derived with Eq. 5. Here we assume that the effective area for $\nu^{'}$s is proportional to $\mathrm{N_{scale}}$. The results for $E_\nu^s = 10^9$ and 10^{10} GeV are shown in Fig. 2. Enhancing the charged current cross-sections by more than a factor of 30 for $E_\nu = 1$ EeV (10^9 GeV) is disfavored if the astrophysical neutrino intensities are around $\sim 10^{-7}$ GeV cm^{-2} sec^{-1} sr^{-1}, the expected range of the GZK cosmogenic neutrino bulk. Note that neutrino-nucleon collision with $E_\nu = 1$ EeV corresponds to $\sqrt{s} \sim 40$ TeV and the present limit on $\sigma_{\nu \mathrm{N}}$ would place a rather strong constraint on scenarios with extra dimensions and strong gravity, although more accurate estimation requires studies with a model-dependent approach which implements the cross-sections and the final-state particles from the collision predicted by a given particle physics model in the neutrino propagation calculation. Taking into account uncertainty on the astrophysical neutrino fluxes, any model that increases the neutrino-nucleon cross-section to produce charged leptons by more than two orders of magnitude at $\sqrt{s} \sim 40$ TeV is disfavored by the IceCube observation. However, we should point out that the IceCube 2007 data could not constrain the charged current cross-sections if the intensity of cosmic neutrinos in the relevant energy region is fewer than $\sim 10^{-8}$ GeV cm^{-2} sec^{-1} sr^{-1}, approximately an order of magnitude lower than the predicted cosmogenic neutrino fluxes discussed in the literature. Absorption effects in the earth becomes sizable in this case, resulting in less sensitivity to the cross-section. This limitation will be improved for larger detection area of the full IceCube detector.

Fig. 3 shows the constraint when only the NC cross section is varied. Enhancement of $\sigma_{\nu \mathrm{N}}^{NC}$ by a factor beyond 100 at $\sqrt{s} \sim 40$ TeV is disfavored, but this strongly depends on the cosmic neutrino flux one assumes. Because the NC interaction does not absorb neutrinos during their propagation though the earth, even the case when the neutrino flux is small could bound the cross-section, but the limit becomes rather weak; the allowed maximum enhancement factor is an order of $\sim 10^3$.

IV. Summary and Outlook

The IceCube 2007 observation indicated that any scenario to enhance either the NC or both NC and CC equivalent cross-sections by more than 100 at $\sqrt{s} \sim 40$ TeV is unlikely if the astrophysical neutrino fluxes are $\sim 10^{-7}$ GeV cm^{-2} sec^{-1} sr^{-1} in EeV region. A study of constraints on the model-dependent cross-sections predicted by the theories of the black holes creation with extra dimensions is underway with a dedicated treatment of final state particles produced from the black hole evaporation.

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